Measuring the *unmeasurable*: Cost-benefit analysis for new business start-ups and scientific research transfers

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Abstract:

Public laboratories frequently need to assess the economic impacts of two common types of technology transfers: new business start-ups and scientific research transfers. However, it is quite difficult to measure economic impacts for these two kinds of transfers because they generally involve expected future sales or the flow of intangible knowledge. Using two case studies from Sandia National Laboratories, we demonstrate in this paper an approach by which such cost-benefit estimates can be constructed. In particular, we illustrate how to estimate benefits when company (or industry) data do not exist or must be held confidential. Our cases relate to plasma thermal spray technology and polycrystalline diamond compact drill bits.

Keywords: technology transfer | start-ups | scientific research transfer | research and development

Article:*

INTRODUCTION

Public laboratories are under increasing pressure to document the effectiveness of their public research dollars. The R & D competitiveness policies of the 1980s have been underscored in the 1990s by more widespread budgetary concerns about the accountability of public funds. For example, accountability issues underlie the Competition in Contracting Act of 1984 (P.L. 98-369), the Chief Financial Officers Act of I 990 (P.L. 101-576), and the Government Performance and Results Act of 1993 (P.L. I 03-62). As a result, public R & D evaluation is shifting dramatically toward outcome and impact assessment as opposed to the more intermediate technology output evaluations.[1]

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[1] Public Accountability was also emphasized in the I 993 National Performance Review report, in which the importance of measuring results rather than inputs was reinforced. Relatedly, the Task Force on alternative futures for the Department of Energy National Laboratories reported (in the "Galvin" Report) that "there is a perception that

The portfolio of research and technology transfer undertaken in public laboratories is diverse and represents many activities that cannot be easily subjected to impact evaluation. Two types of transfers are common and particularly problematic in this regard: new business start-ups resulting from the transfer of a specific technology or technique and scientific research transfers that result in new or improved products/processes. While these are common types of transfers, they may be the most difficult to evaluate from an economic perspective, for two key reasons.

First, in the case of a start-up, benefits occur in the future. Assessments must therefore be prospective. Second, scientific research transfers are almost inevitably intangible, hard to link to a specific laboratory project, and usually require additional R & D by other institutions. Assessment of scientific research must therefore trace nearly invisible *flows of knowledge* and apportion final benefits to either different R & D performers or different stages of the R & D process. Both prospective and flow evaluations are difficult simply because their impacts are hard to measure (and frequently alleged to be *unmeasurable).* Still, these types of transfers may be the most important for laboratories to evaluate, since they are most representative of the scope of laboratory activities and could have the greatest economic impacts.

The purpose of this paper is to illustrate a method for conducting a cost-benefit analysis for each of these two common (and empirically problematic) forms of technology transfer. We present two case studies of technologies developed at and transferred from Sandia National Laboratories.[2] The first study, on plasma spray technology, demonstrates techniques that can be used to evaluate the future economic impacts of new business start-ups. The second study, on polycrystalline diamond compact drill bits, shows how to link scientific research flows to the commercial marketplace and assess impacts after they have occured. While interesting in their own right from a technological perspective, each case illustrates how to overcome the difficulty associated with measuring seemingly *unmeasurable* benefits. As such, the cases provide guidance for those required to undertake similar evaluations.

Quantifying the Benefits from Technology Transfer

The methods we use to quantify the economic benefits of technology transfer involve a mix of (l) traditional case study analysis, (2) creative metrics, and (3) conventional cost-benefit analysis. All three approaches are necessary. Public technology transfer evaluation typically requires intensive information gathering (qualitative case analysis), quantifying subjective information or impacts when the best data are not available (creative metrics), and formal analysis of the information and data collected (here, conventional cost-benefit analysis).

Each of our two cases employ different creative metrics and slightly different dimensions of cost-benefit analysis. The precise details are described within the context of the cases. However, they do share a common framework in two respects. First, both use the same case study

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the U.S. government is spending significant resources on the development of new technologies but that American industry is not reaping the rewards of that investment" (p. 46).

[2] Sandia National Laboratories is a government-owned, contractor-operated multiprogram engineering and science laboratory. It is operated for the U.S. Department of Energy by Sandia Corporation, a subsidiary of Martin Marietta Corporation.

methodology. Sandia personnel and industry officials were interviewed[3] extensively about the history and nature of the technologies, R & D programs, mechanisms for transfer, relationships between the laboratories and industry, nature of the industries, and industrial impacts. The. industrial trade literature was reviewed to explore (a) the structure of the industry that the technology was transferred to, and (b) market dynamics of the commercial innovations resulting from the transfers. Empirical case information was obtained from public and private sources- Sandia officials, industry representatives, and published trade documents.

Second, our cost-benefit analysis examines first-, second-, and third-order economic impacts.[4] In most evaluation studies of public sector research, benefit analyses have focused on the first level, that of the adopting industry.[5] However, because economic activity has diffusion, spillover, and multiplier effects, the benefits of technology transfer can be enjoyed outside the boundaries of the initial recipient of the transfer. The potential benefits of technology transfer can therefore be classified according to the level at which they are expected to occur.

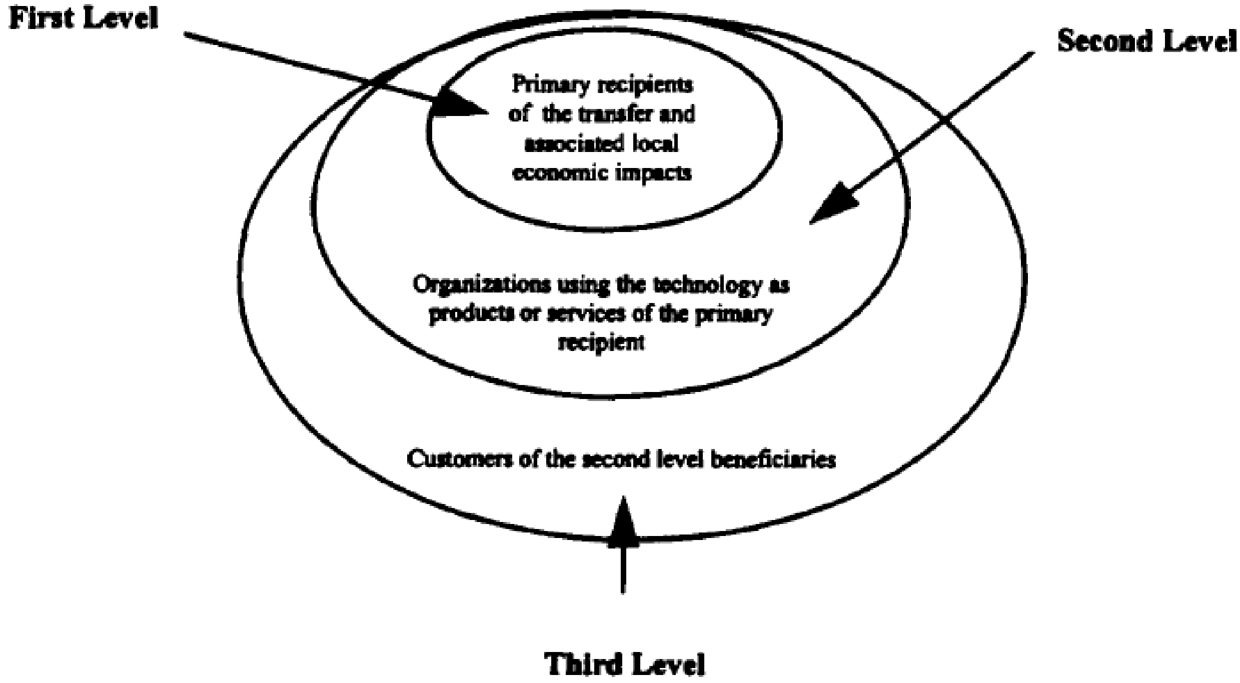

Figure 1. Levels of economic benefit

Figure l illustrates each of the three economic levels of impact evaluated in our case studies. First-level benefits are those that accrue directly to the company, companies, or industry which bear the primary responsibility for commercializing the transferred technology. Also included in the first level are the benefits to a local economy which result from the acquisition and commercialization of technology by a local enterprise. Second-level benefits are those realized by organizations doing business with the initial user of the technology. These "down stream"

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[3] The interviews were conducted by Link, Falcone, and Bozeman. See Falcone (1995).

[4] The rationale for this "levels" approach may be found in Link (1996a) and Link (1996c).

[5] Link (1996b) summarizes a number of such studies conducted for the National Institute of Standards and Technology.

beneficiaries may be end-users of the product, or they may be manufacturers using the technology as elements of their own products. Third-level benefits are those that are realized by the customers of the second-level beneficiaries.

For both practical and political reasons, caution should be used when calculating benefits beyond their first-order impacts. Very simply, benefits are often hard to estimate and it is easy to neglect the costs associated with benefits at the second and third levels of impact. Because of this, cost-benefit estimates beyond the first order of impact may easily be under- or overstated.

Keeping estimates within the realm of plausibility is critical for political reasons: Congress and parent headquarters of laboratories are becoming increasingly intolerant of what they perceive to be inappropriately inflated benefit estimates or numbers that are simply too "high" to be believed. A degree of conservatism is advised for anyone undertaking a cost-benefit assessment of public technology transfer — policymakers and interpreters of a laboratory's evaluation are not likely to believe numbers that appear to be exaggerated.

MEASURING THE IMPACTS OF A NEW BUSINESS START-UP: PLASMA SPRAY TECHNOLOGY

The case we use to demonstrate cost-benefit analysis for a new business start-up is the transfer of plasma spray technology from Sandia National Laboratories to Fisher-Barton, Inc., a Wisconsin-based manufacturer of lawnmower blades, wood chippers, and agricultural equipment.[6] The transfer occurred during 1988-89 when Fisher-Barton sent one of its engineers to conduct research at Sandia. After working with the technology for several years internally, Fisher-Barton created an independent subsidiary, Thermal Spray Technologies (TST), which opened as an establishment in 1994. The two principle difficulties in estimating benefits for this case relate to estimating *future* benefits and dealing with the confidentiality of all the business data obtained.

Plasma spray itself is one of three major types of thermal spray, a generic term for a group of coating processes used to apply metallic and non-metallic coatings. Plasma is a gas in an excited state, and it is used as an energy source to heat coating materials (in powder, wire, or rod form) to a molten or semi-molten state. Plasma can generate temperatures higher than those obtained with any combustion process, making it an efficient process for spraying very high melting point materials, like ceramics. For example, some ceramics melt at around 4000° F. Using plasma as a heat and propulsion source, molten droplets can be sprayed onto items that melt at much lower temperatures, coating objects while they remain cool at temperatures less than 200° F. The purpose of spraying such a high temperature coating on a component is to make it wear longer by changing its surface chracteristics.

Thermal spray technology has been used since the turn of the century, and Sandia National Laboratories began research on plasma spraying in 1967 for defense applications (primarily weapons). The laboratory's R & D in this area continues, and applications of the technology have

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[6] Founded in 1973, Fisher-Barton is the largest manufacturer of lawnmower blades in the world, with a 50% share of the available world market. (Some companies that produce lawn and garden products also manufacture their own blades; this "captive" production is not considered part of the open market.)

been expanded to include solar energy and civilian industrial uses, including the new-business start-up presented here.

Transferring Plasma Spray Technology from Sandia

In the mid-1980s, Fisher-Barton had been investigating ways to make their lawnmower blades last longer and had explored plasma spray technology for this purpose — its knowledge of the technology was gained through the graduate studies of one of its engineers, Bill Lenling. When the company quickly discovered that lawnmower blades were not suitable for plasma spray, its chipper blades were next for consideration. In late 1987, the president of Fisher-Barton, Dick Wilkey, was at Sandia to inquire about general metallurgical questions when he learned *by chance* about Sandia's expertise in plasma spray technology. Within a year, Fisher-Barton applied for and received a small business technology transfer grant of $57,000 from the U. S. Department of Energy.[7] The grant enabled Lenling to conduct research at Sandia from June 1988 to September 1989. His work for the company related to plasma spray for chipper blades, but he also obtained valuable knowhow about the plasma spray process. According to Wilkey, the greatest value to Fisher-Barton from the Sandia experience was in fact the knowledge gained about how to scientifically analyze various coatings and how to determine the optimum coating for a specific application.[8]

Fisher-Barton ultimately could not use plasma spray for its chipper blades, either. However, the knowledge of plasma spray science and techniques it obtained through the R & D grant led to the creation in 1989-90 of a plasma spray division within Fisher Barton for other internal applications. By 1993, this division had enough of an *external* client base that it was spun-off as an independent company, Thermal Spray Technologies. This new enterprise officially started up in 1994.

Quantifying the Benefits and Costs of the Plasma Spray Transfer

One particular feature of this case makes the cost-benefit analysis somewhat easier than the one to follow on polycrystalline diamond compact drill bits — the transfer of know-how was, to our knowledge, solely to Fisher-Barton, and the. know-how obtained was rather exclusively developed by Sandia National Laboratories. This is a typical characteristic of start-ups and spinoffs resulting from public laboratory technology, and it makes linking economic impacts to the laboratory more direct.

However, there are a number of other characteristics which are also common to start-ups, but which complicate cost-benefit analysis. These include:

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[7] There was an initial $42,000 grant and a follow-on grant of $15,000 to supplement Lenling coming to Sandia for 15 months, beginning in June 1988. According to the terms of this grant, Fisher-Barton paid Lenling's salary while he was in residence at Sandia; the grant gave him $7500 in living expenses and the remainder went to the laboratory to cover Lenling's overhead expenses.

[8] We are thankful to an anonymous referee for pointing out that we ignore benefits that could accrue back to Sandia from feedback from Lenling. We did ignore this due to no quantifiable information. There are knowledge spillovers as well that will occur from the dissemination of knowledge via articles and patents.

1. The recentness of the business. TST's 1994 start-up date meant that sales had yet to be realized at the time this analysis was undertaken. All benefit estimates therefore had to be prospective.
2. Most companies, whether directly or indirectly, benefiting from thermal spray technology requested that their data be kept confidential or else withheld their data from the study.[9] All benefit estimates were therefore self-assessment measures (expressed preferences) rather than the revealed preferences of the market, for which objective data would otherwise be available.[10]
3. TST is a small high tech start-up which traditionally has higher value-added than mature businesses. However, mature businesses typically have larger regional multiplier effects. Local economic impacts were therefore not calculated with traditional regional multipliers, but with a high tech manufacturing multiplier.

The potential benefits resulting from the transfer of plasma spray technology to Fisher-Barton are classified below according to the level at which they have or are expected to occur. The first-level benefits are those that directly accrue to Fisher-Barton and the local economy as a result of Fisher-Barton identifying, acquiring, and utilizing the Sandia-based technical knowledge. Second-level benefits are those realized by organizations that embody plasma spray technology through the services of TST. Two of TST's customers were willing to provide information for the study and constitute the benefit estimates at the second level. Another two of TST's customers[11] were *not* willing to discuss their own business, but would speculate about the impacts of their thermal sprayed products for their *customers.* The estimates by these two companies for their customers constitute the thermal spray benefits at the third-level.

First-level Benefits

At the first level are the direct benefits to Fisher-Barton from acquiring and using the Sandia-based technical knowledge and the multiplier effects of this acquisition on the local Wisconsin economy. The most visible first-level benefit has been the profitable formation of TST by Fisher-Barton.

Because Fisher-Barton/TST are the sole beneficiaries of the transfer, there is no way company data could remain confidential in an impact evalutation. This problem of confidentiality was surmounted by assuming that TST, like other small companies, would realize a five-fold recovery of its initial costs to acquire the technology and start-up its business. This recovery corresponds to a capitalization rate of 20%, which is consistent with Internal Revenue Service guidelines on business valuation in IRS Ruling 68-609. Fisher-Barton was willing to provide data on their capitalized investments, which were just over $1 million in salaries and

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[9] In prospective studies where a number of companies, in a variety of industries, have adopted the technology, confidentiality can be maintained by aggregating across the self-assessment measures. This was not possible here.

[10] These limitations noted, prospective studies are useful for a public laboratory for at lease two reasons: they can establish a benchmark for a follow-on study and they can provide useful "early-on" management feedback to those in the laboratory about the application scope of the technology. See Link (1996b).

[11] All four of these TST customers represent more than half of TST's sales.

equipment.[12] Using this 20% capitalization rate, Fisher-Barton's net profits can be estimated at $5 million.[13]

Other first-level benefits associated with TST's use of Sandia's technology include the regional economic development impacts created by the establishment of TST in Wisconsin. There are regional benefits associated with the formation of any new company as well as with the output of existing companies; generally, these benefits include increased employment and the increase in spending associated with greater local employment.

Estimating the local impact of a small high tech startup is complicated by the differential impacts of both small businesses and high-tech businesses compared to their larger, more mature industrial counterparts. Although the U.S. Department of Commerce multiplier for the thermal spray industry in Wisconsin is about 2.0,[14] the Economic Research Services (ERS) group within the U.S. Department of Agriculture estimates that there is a 1.5 times multiplier effect on a regional economy from new technology-based manufacturing companies. In other words, for every $100 of sales there is a $150 impact on the growth of the region.[15] We selected the 1.5 multiplier because it was more appropriate to TST as a business and not an unreasonable point estimate (it is also a more conservative estimate than the Department of Commerce multiplier). Based on TST's reported 1994 sales of just over $1 million,[16] the current dollar impact of the company on the regional economy is estimated at $1.5 million. Again capitalizing this amount at 20%, *the present value of expected future benefits* to the regional economy associated with TST acquiring and using Sandia's plasma spray technology is estimated at $7.5 million. Total first-order benefits of the the transfer of Sandia thermal spray technology to Fisher-Barton/TST are $12.5 million.[17]

Second-level Benefits

Second-level benefits are by definition those that accrue "down stream" from the initial user of the technology. Second-level of benefits associated with Sandia's public good technology can be

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[12] This financial information was provided by Dick Wilkey, president of Fisher-Barton.

[13] We are aware that this first-level benefit estimate is directly tied to an assumption of a 20% capitalization rate. Absent better data, we view this percentage as a point estimate with precedent. As such, the reader can decide what element of bias may be introduced by this.

[14] Actually, identifying the proper industrial multiplier is not an easy task for the thermal spray industry: it has not been classified into the SIC system. The U.S. Department of Commerce (1992) estimates a state-wide final demand (e.g., state domestic product) multiplier specific to Wisconsin of 1.92 for the fabricated metals industry and 2.07 for the electric and electronic equipment industry. Note that the more mature the company or the industry, the larger the multiplier.

[15] This information came from Dr John Redman, now of the Manufacturing Extension Program within the U.S. Department of Commerce, and formerly with ERS and involved in the calculation of this multiplier. According to Redman, the 1.5 multiplier was a typical result from the IMPLAN regional input-output model for technology-based manufacturing companies within a local region.

[16] This sales estimate was also provided by Dick Wilkey.

[17] Although not estimated as part of this study, it is important to point out that there are intangible benefits associated with Sandia's research. According to Bill Lenling, four scientific papers were published as a result of his work with Sandia. (He co-authored these papers with scientists from Sandia.) In addition, Lenling made five presentations at professional association meetings on plasma spray and received one patent from his research while at Sandia. A second one is pending. Assigning economic value to these first-level intangible benefits is not appropriate for cost-benefit analysis.

approximated in terms of the increased net profits to those organizations that have their products sprayed at TST as opposed to having them sprayed at other thermal spray companies. In other words, the economic benefits associated with Sandia's thermal spray technology to TST's customers is measured in terms of the value of their increased market position (hence increased sales and increased net profits) as a result of utilizing Sandia's technology through TST.

At present, there are four major companies[18] that have their products sprayed at TST and were willing to participate in an interview as part of this case study. Two companies were willing to estimate benefit values based on their experience with plasma spray technology and their knowledge of their company's planning. The other two companies were not willing to discuss economic issues due to concerns about confidentiality. However, they were willing to speculate about the economic benefits that can be traced directly to plasma spraying that have been, or are expected to be, received by their customers. The information obtained from these latter two companies is discussed in the following section on third-level benefits. Of the two TST customers willing to provide benefit estimates for their own businesses, one company produces integrated circuit brackets (Company A) and the other company produces bicycle rims (Company B).

Company A is a domestic auto manufacturer needing a coating on a bracket that holds a heat-producing integrated circuit. The integrated circuit is attached to the engine and transmission controls of the company's 1994, 1995, and 1996 automobiles (of a particular type). If the bracket coating did not provide sufficient electric isolation with heat transfer, then the controller could fail and the automobile would stall. Company A investigated a number of alternatives to TST's ceramic coatings, but the company was experiencing a 1% failure rate with the best of the alternative technologies. TST's ability to apply a ceramic coating to the brackets with a good tolerance for flatness reduced the field failure rate from l to 0%. According the project engineer at Company A, there have been no field failures in their automobiles since contracting with TST.

As noted earlier, the prospective nature of this case study requires that self-assessment data be used for the analysis. After hearing about Company A's experience with TST coatings during the telephone interview (and assuming that the project engineer's estimate of a reduced failure rate from 1 to 0% is accurate), two benefit estimates were discussed. The first related to the projected number of automobiles that would benefit from the use of plasma spraying; the second related to the projected cost savings of avoided repairs on failed integrated circuits.

The project engineer estimated that 500,000 automobiles would use plasma-sprayed brackets in each of the three years 1994, 1995, and 1996.[19] Plasma-sprayed brackets are thus expected to reduce the number of part failures from 5,000 to O in each of those years. Based on previous experience (rather than accounting data), the engineer estimated that the company would save $50 in repairs per failure, net of the cost of ceramic coating, or $250,000 ($50 times 5,000) in each of the three years 1994, 1995, and 1996. Absent any company-specific information on the repair price increase in 1995 or 1996 or of the company's cost of capital with which to estimate a

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[18] These four companies represent more than 50% of TST's sales; company contacts were provided by Lenling.

[19] When asked about this point estimate of 500,000 automobiles, the project engineer stated that this was the number being used for internal company projections.

discount rate, it is assumed here that the point estimate of $250,000 is a present value estimate.[20] The total *net present value benefit* to Company A from TST spraying is therefore estimated at $750,000.

Company B is a domestic manufacturer of high performance racing, mountain, and road bicycles (which retail for well over $2000). Company B began to have their wheel rims ceramic coated in 1995 in order to compete more effectively in the world market and to provide them with a market advantage against their major domestic competitor, who currently uses an inferior non-plasma sprayed rim. The project engineer for Company B believed that with a plasma-sprayed ceramic rim, the company would be able to improve its domestic market share.

During the telephone interview, the project engineer estimated that through its relationship with TST, Company B could produce its own rims at a cost savings of $80 per set of rims, as opposed to purchasing a foreign company's rims for their bicycles. Based on the engineer's projected sales of 30,000 bikes per year for 1995 and 1996, Company B is expected to save $2.4 million per year ($80 times 30,000) in rim costs as a direct result of utilizing plasma spray technology. It was the project engineer's opinion that two years is the expected life of such rims; after that time new bicycle technologies are expected. Because production of these rims had not begun at the time of this study, this cost saving figure is speculative; the potential net present value benefits based on this point estimate are, however, $4.8 million for the technological life of the bicycle rim.

There is one other *potential* second-level benefit to Fisher-Barton/TST from their acquisition of Sandia's plasma spray technology: that of "impulse" drying for the pulp and paper industry.[21] The cost savings to this industry by plasma-spraying drying rolls used in the manufacture of paper is potentially $2 billion per year.[22] Although there are quantifiable estimates and projections that can be made regarding the social benefits of plasma spraying to impulse drying, we have refrained from generating a benefit estimate for two reasons. First, there has yet to be a commercial application of impulse drying and the technology will not be available to the industry until at least 1999. Second, savings benefits are currently based on very limited laboratory tests and prototypes; operational savings could prove to be very different.

Third-level Benefits

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[20] This assumption is analogous to assuming that the percent increase in the cost of repairs equals the company's cost of capital. That is, the inflation factor and the discount rate cancel each other. The problems associated with discounting were also discussed during the telephone interview, and it was the opinion of the project manager that the present value assumption was reasonable in the absence of any additional information, and probably conservative given the companies history of repair cost increases.

[21] Impulse drying has been prototyped by TST in conjunction with the Institute of Paper Science. Scientists at the Institute believe that the plasma spray technology demonstrated by TST has shortened the R & D-to-market cycle by two years for impulse drying (projected at 5 years).

[22] Engineering estimates indicate that about 50% of the paper made in the U.S. can be dried with impulse drying. Energy savings will be $5 per ton of paper produced, and pulp savings will be $20 per ton of paper produced. See Orloff (1992), Orloff and Lindsay (1993), and Orloff and Sobczynski (1993). These savings are applicable to approximately 80 million tons of paper a year.

Telephone interviews were conducted with the other two customers of TST in an effort to approximate the benefits realized by those companies' customers that utilize their TST-coated products. One customer produces coater blades and the other customer produces pump seals. A significant effort was made to structure the interview discussions in such a way that the interviewee would directly associate customer benefits with plasma spray technology as manifested on the products sold.

Coater blades are used for finishing paper. In the final stages of production, processed paper passes through a number of machines and then coater blades scrape residue from the paper to give it a smooth finish. Ceramic-coated blades benefit the paper industry because they last longer than traditional steel blades, reducing the number of times the production process has to be stopped in order to replace worn blades. Company C is now the only domestic company selling coated blades to the paper industry, and according to the national sales manager of the company, the knowledge transferred to TST from Sandia has advanced the quality of their blades and thus advanced the state of finishing in the paper industry as a whole (Company C sells to 35% of the 350 paper mills in the U.S.).

Other companies will eventually begin to produce coated blades as other thermal spray companies improve their technology and processes. The manager at Company C estimated that his company has a two year lead on other companies because of Company C's use of plasma spraying. When asked to estimate the average net cost savings per mill due to reduced down time, the point estimate he gave was $20,000 per year per mill. If his expert opinion is correct — that other companies will be able to provide coated coater blades of comparable quality to TST's by 1996 — then this total net present benefit[23] of $1.64 million savings ($20,000 times 41 mills in 1995 and 1996) to Company C's customers is short-lived, realized only in 1994 and 1995.[24]

Regarding pump seals, Company D manufactures pumps that are used primarily in the food processing industry. This company coats its pump seals and shafts in order to reduce failure rates. According to Company D's buyer/analyst, TST coating technology has decreased failure rates among their customers by 100 failures per year. When asked to estimate the average length of down time and the associated economic cost she estimated that down-time was 1.5 days per failure at cost of $2000 per day. If correct, the company's food processing customers are saving approximately $300,000 per year ($2000 per day times 100 failures times 1.5 days per failure) in reduced production process maintenance. No other information was provided in terms of lead times over competitors, so total net present value benefits cannot be estimated.

Total Quantifiable Benefits and Costs

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[23] The length of the benefit is tied to the period that Company C's customers enjoy an advantage over their competitors. Additionally, as above, these estimates are viewed at present values ($1994) given no additional information, although the interview discussions were in constant dollar terms.

[24] The national sales manager at Company C went on to say during the interview that TST's application process is still improving, and by 1996 the replacement life of a TST-coated blade (which is based on Sandia technology) could increase from 5 times to 20 times that of a steel blade. If his expectation is realized, then the cost-saving to the industry from using TST's will extend beyond 1996, and Company C might also increase it market share since it will remain technologically ahead of its competition. The social benefit estimate of $820,000 in each of the years 1994 and 1995, does not take into account these possibilities.

The discussion above is important for several reasons. First, it provides a sense of the widespread impact that the transfer of plasma spray technology has had at several economic levels. Second, it demonstrates the obstacles that are often confronted in cost-benefit analysis, and shows that even the best estimates may be relatively speculative. Table 1 provides a summary of all the benefits that have been reviewed for this case: first order benefits alone are estimated at $12.5 million, and if the as-yet-unrealized benefits to the paper industry are taken into account, economic benefits of TST plasma-spray services could amount to well over $2 billion a year.

Table 1. Total estimated benefits from thermal spray technology

Level of benefit/recipient	**Total estimated $1994 benefits**
First level	
Fisher-Barton, Inc./Thermal spray technologies	$5 million
State of Wisconsin regional impact	$7.5 million
Second level	
Company A, brackets for integrated circuits (autos)	$750,000
Company B, bicycle rims	$4.8 million
Pulp and paper industry	insufficient data to estimate
Third level	
Company C, coater blades for paper finishing	$1.64 million
Company D, food processing pumps	insufficient data to estimate

With respect to costs, Sandia began its research on plasma spray technology in 1967. While the specifics of that early research remain classified, Sandia's best estimate of the direct cost to operate the program is 0.8 person years of effort from 1967 through 1983, or $100,000 (in 1994 dollars) per year; and then 2.5 person years of effort from 1984 through 1988 — the time the technology transfer to Fisher-Barton began — or $400,000 per year (in 1994 dollars). The total of these estimates is $3.7 million.[25] Associated with these Sandia costs is the $57,000 cost of the Department of Energy's technology transfer grant to Bill Lenling of Fisher-Barton in 1988-1989. The present value ($1994) of these grant costs (deflated to 1994 by the Consumer Price Index), is $70,600, bringing total costs to approximately $3.8 million.[26]

These estimates suggest a first-level benefit-to-cost ratio of 2-to-1; that is, $7.5 million in first-level benefits to $3.8 million in costs. Although we did estimate second- and third-order benefits to illustrate cumulative economic impacts, these secondary and tertiary estimates were viewed as overly speculative for use in this cost-benefit analysis. Our reason for viewing these benefits as overly speculative is not that they were based on expressed preferences, but because no conclusive opinion or evidence could be given as to their accuracy. We had significantly more confidence in the reliability of the first-level benefits, and thus erred on the side of a conservative estimate. Second- and third-level benefits were provided to highlight the technology background and diffusion.

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[25] This cost information was approximated by Mark Smith of the Thermal Spray Research Laboratory at Sandia (17 years at $100,000 per year plus 5 years at $400,000 per year).

[26] This is based on a 1988-89 CPI mid-point estimate of 121.2 and a 1994 CPI of 150.1. A valid case could be made that a fully-burdened R & D deflator should have been used in this calculation to bring forward previous Sandia personnel costs. We are not aware of any such published deflator that would be applicable to this study, but because Sandia salary increases are tied, in part, to a cost-of-living index, our use of the CPI is not expected to bias the conclusions of the study.

MEASURING THE IMPACTS OF FUNDAMENTAL RESEARCH TRANSFERS: POLYCRYSTALLINE DIAMOND COMPACT BITS

The case we use to demonstrate cost-benefit analysis for fundamental research is the transfer of polycrystalline diamond compact (PDC) drill bit knowledge from Sandia to the oil well drilling equipment industry. The first explicit transfer of PDC science occurred during the period 1973-77, when General Electric (GE) worked directly with Sandia to improve the performance of prototype PDC bits (the bit was first commercially introduced by GE in 1977). After 1980, there was relatively rapid diffusion of the bit throughout the drilling industry, and technology transfer between Sandia and the private sector continued until the late 1980s. The two principle beneficiaries of PDC technology are the manufacturers of oil well drilling equipment (through increased sales to oil companies and drilling contractors) and the oil drilling industry (through cost savings).

There are several major difficulties that complicate benefit estimates in this case. First, fundamental research transfers do not represent the movement of discrete technologies or even applied know-how (as in the previous case on plasma spray). Consequently, it is hard to trace the flow of scientific knowledge *and* tie that knowledge to events in the commercial marketplace. Second, the most critical benefit data on cost savings to the oil drilling industry simply were not available. Third, the oil drilling equipment manufacturers contributed significant amounts of their own time and money to transform PDC scientific knowledge into usable commercial products.

PDC bits are one of several types of drill bits used for oil and gas well drilling. Drillers confront sticky clays, soft shales, brittle limestones, and so forth when drilling oil and gas wells, and different types of bits are used for different types of rock and earth formations. The technological virtue of PDC bits is that their cutting surface is covered with a layer of synthetic diamonds, which increases their wearability and shears rock differently than conventional bits. PDC bits radically changed the speed at which oil wells can be drilled and are regarded as a "revolution" (Muhleman, 1984) by the industry.

Sandia National Laboratories' Geothermal Division initially became involved with PDC bits in the early 1970s. Geothermal energy is potentially a significant source of power, but drilling such wells was then prohibitively expensive — only natural diamond bits can penetrate the hard rock surrounding geothermal deposits, and they do so very slowly. Sandia knew of GE's work on PDC bits and thought its technology might provide the necessary breakthrough in geothermal drilling. At the same time, GE was confronted with a number of commercial development problems since its bit was failing regularly in field tests.

Sandia contributed to the initial development of PDC bits (and getting them to market) in several ways: by providing R & D contracts to GE for wear and friction tests, by conducting in-house fundamental research on bit mechanics and hydraulics, by testing PDC bits in the field, by resolving some of the technical problems the bit exhibited, and by developing a computer code to aid bit design. Sandia's PDC R & D program ran from 1973 to 1986, and throughout the 1980s scientific knowledge was continuously transferred to the private sector.

Transferring PDC Bit Technology from Sandia

The PDC bit "technology" transferred from Sandia was actually scientific *knowledge* about the physics and hydraulics of PDC bit operation, force, wear, and failure patterns; discrete technology transfer only occurred in the form of a computer code to aid bit design. By and large, knowledge transfer occurred through word-of-mouth and the 42 professional presentations and publications by Sandia scientists on PDC bits. The "invisible college" of research professionals and the public domain were thus the primary modes of transfer.

Intangible knowledge flows naturally present challenges for linking the scope of Sandia's efforts to events in the economy. Tracing Sandia's impact on the market was accomplished through intensive case study research — nearly 100 industry experts and trade publications were consulted to construct the analysis for this case. Sandia's role was established in two ways: first, by the explicit acknowledgement of industry experts, and second, by comparing the commercial innovation/product cycle of PDC bits to Sandia's programmatic efforts.[27] What becomes apparent is that Sandia played a clear, trackable, and acknowledged role in the development of PDC bits and it did so in three ways: (1) initial development of the bit and getting it to market, (2) correcting serious flaws in bit performance after it had been commercially introduced, and (3) overcoming ongoing limitations to the bit after it had become a standardized industry product.

Industry acknowledgement came in the form of both oral interviews and industry documents. For example, many officials openly credited Sandia for the progress of PDC bits and pointed out that it was the *publicness* of this effort that made a difference. Interviews and company product literature demonstrated that about half the industry used and built upon Sandia's computer code. With respect to publications, the editor of *Drilling Engineering* (the journal of the Society for Petroleum Engineers) picked a Sandia PDC article as "best of issue," and praised it for its comprehensive, detailed explanations (Millheim, 1986). Relatedly, Sandia's senior scientist on the PDC bit program was nominated for a prestigious professional award by an industry official.[28] As one industry expert put very simply, "everyone used papers from the labs at Sandia".

While Sandia's PDC bit knowledge was clearly used by industry, the question remains as to what market impact it had. The product cycle model common to innovation analysis is a useful tool for answering this question. Product cycle models typically have three stages: (1) the prototype-to-market stage and the associated "debugging" that occurs in the early commercial years of that innovation, (2) the diffusion stage in which the innovation is progressively improved and gradually becomes a standardized industry product, and (3) the mature stage in which the innovation becomes a fully standardized product, its applications are well understood, and it has achieved virtually complete adoption by industry (Freeman, 1986). PDC bits have already moved

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[27] It is important to get confirmation of industry impacts from a variety of sources. A study by one of the authors revealed that, in spite of the claims by a public agency and its R & D contractor, the commercial innovation in question resulted from a completely independent effort by another organization. See Papadakis (1991).

[28] This official stated in his nominating letter: "From my point of view as a drill bit manufacturer, I think the research which David Glowka has presented at SPE meetings the last several years represents some of the most important scientific work related to drilling technology. I would like to nominate him for the 1985 SPE Drilling Engineering Award" (letter from Reed Tool Company to Sandia).

through a complete cycle: commercial introduction took place between 1977-82; diffusion and debugging ocurred primarily from 1982-86; product standardization and virtually complete adoption occurred between 1986-92.

Sandia may be linked to all three phases of the PDC bit cycle. First, GE consistently credits Sandia with getting the bit to market (and debugged) several years earlier than GE would have been able to on its own. This is a critical point for yet another reason: PDC bits were introduced at the beginning of a drilling boom, and intense industry demand compensated for the poor field reputation of PDC bits. (Since the drilling industry is highly risk averse in its adoption of new technologies, only a clear "winner" or protracted high demand can successfully pull an innovation into this mature industry.) Notably, the drilling market "busted" in the mid-1980s, and had PDC bits been introduced after about 1980, they would undoubtedly have failed in the market.[29]

Second, Sandia was regularly credited in interviews and writing for its contribution to bit performance during the critical diffusion stage. For example, in an industry article summarizing bit advances and breakthroughs from 1981-1986, about half of the citations are to Sandia's work (Mahlon et al., 1987). Company product literature identifies Sandia's computer code (released in 1982) as a key contribution to bit performance. Altogether, 22 scientific papers were published or presented during 1980-86.

Third, Sandia's expertise cumulated into a final, highly sophisticated computer code for modelling bit forces and wear. This software was issued in 1986 (the last year of Sandia's PDC program) and coincides with the mature phase of the bit's product cycle. The second code is regarded by industry as the breakthrough which enabled the development of a whole new generation of PDC bits (called "antiwhirl" bits).

This somewhat extensive review of the relationship between Sandia's R & D program and the commercial innovation cycle is important for a few reasons. First, it demonstrates a model for determining *how* intangible knowledge flows may be linked to specific economic markets and outcomes. Second, it reveals that Sandia's PDC bit research was a critical precondition to market success for the bit (it accelerated the product-to-market cycle in a fortuitous way). Third, it establishes that Sandia's technical efforts were intrinsic to product improvements during the diffusion stage of the PDC bit's product cycle, a stage recognized to be the most important economically (Stoneman, 1983). Finally, Sandia had a sustained impact on the industry by enabling a new PDC bit product cycle, the antiwhirl generation of bits. For all of these reasons we may comfortably credit Sandia (in some part) for the economic benefits that occurred throughout the first product cycle of PDC bits, roughly 1977-92.[30]

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[29] PDC bits had a lengthy debugging period after they were introduced; it lasted from about 1977-82. During this time the bit did not enjoy a good field reputation, and only the general shortage of drill bits kept sales going. If the bit had been introduced in 1980, the 5-year debugging would have overlapped with the drilling bust. Without that demand, the bits would have failed in the market.

[30] Benefits cannot be projected infinitely into the future - they are appropriately estimated only for the period in which the conversion from one technology to another is taking place. Once a technology is fully diffused and hence becomes "best practice," the differential benefits associated with its use disappear.

Quantifying the Benefits and Costs from PDC Knowledge Transfer

Although the level of impact is clear-first-level benefits accrue to the industry that manufactures and sells PDC drill bits, second-level benefits accrue to the drilling industry by virtue of using the new technology-several elements of this case make estimating benefits particularly problematic. First, key industry data were sorely lacking and we resorted to several creative metrics to estimate second-level benefits. Second, in spite of Sandia's contribution to the commercial success of PDC drill bits, it isn't clear how much of the total economic benefits we may reasonably apportion to Sandia's R & D effort and its associated costs.

First-level Benefits

The economic benefits of PDC bit knowledge transfer are calculated for the period 1982-1992. As mentioned earlier, full diffusion of the PDC bit throughout both the oil well equipment and drilling industries occurred by 1992; the industry literature suggests that 1982 is the first year a "real" PDC market was established and the diffusion stage began. First-level benefits accrued to the drill bit manufacturing industry (the primary recipient of the transfer) and the local economy. PDC bits were adopted quickly by the equipment manufacturers, and as many as 25 firms have produced these bits. The market is not stable due to ongoing mergers and acquisitions; but altogether about 10-12 companies made these bits in the 1980s and 1990s. For virtually the whole period of benefit estimation, 75% of PDC production was in Texas.

PDC bit sales data were available from published trade documents and industry officials for all years except 1983-87; data for this interval were imputed using arithmetic progression. Total industry sales from 1982-92 amount to $873 million ($1987).[31] Note that these sales are not net of industry costs: although the drill bit manufacturers invested heavily in their own R & D and start-up costs for PDC bits, data on these costs were not available nor was the discount rate for the industry, As a consequence, neither a net cost or a net present value estimate could be calculated for first-order benefits to the industry.[32]

Local benefits can be estimated for the 75% of PDC production that occured in Texas. Using the 1.5 high tech manufacturing multiplier discussed in the plasma spray case,[33] the total local impact of PDC bit production is $982 million ($1987). Based on gross industry sales, total first-level benefits from 1982-92 are therefore $ l .86 billion.

Second-level Benefits

Second-level benefits accrue downstream; in this case, it is the oil/oil well drilling industry that benefits from PDC bits.[34] Indeed, most of the economic impact of PDC technology at this level

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[31] PDC bit sales were converted to constant 1987 dollars using the U.S. implicit GDP price deflator.

[32] The benefit estimate therefore has an upward bias.

[33] The Department of Commerce regional multiplier for the crude petroleum and natural gas industry in Texas is 1.6. We opted for the lower multiplier for the same reason as for plasma spray: PDC bits represent high-tech manufacturing and it is the more conservative estimate.

[34] There are other industries that benefit from PDC bits at this level, principally the coal mining industry. However, benefits for these industries relative to the oil drilling industry are not of consequence and were excluded from the scope of our analysis.

occurs through extraordinary cost savings in oil well drilling. The primary cost of oil well drilling is related to time: rig crews are typically paid by the day, and it can often take *weeks* (and more than a few hundred thousand dollars) to drill a single well. Because PDC bits dramatically reduce the time it takes to drill wells, they dramatically reduce the associated costs as well.

In fact, in the drilling industry bits are selected based on their ability to minimize the cost-per-foot drilled-virtually all industry analysts say that the best way to assess the economic impact of PDC bits is to estimate the cost savings per foot of well drilled. This is simply not possible to do, however, for a variety of reasons that have to do with proprietary data, the geology of wells, the economics of drilling, and the lack of any aggregate industry data that could be used as a reasonably proxy/metric for this cost savings analysis. As a consequence, the following "creative metrics" were used.

First, there are published industry accounts of the total *well* (not foot) cost savings associated with PDC bits. There are 22 such point estimates published in the industry literature; PDC bits yielded a total cost savings ranging from $16,000 to $231,000 per well. These point estimates were used to make an informed, subjective estimate of the total cost savings per well drilled with PDC bits. Assuming that only the most sensational well savings would likely be published, and therefore that many wells would realize cost savings much lower than published accounts, we assumed that *on average, and in nominal dollars,* a well drilled with a PDC bit would realize a $10,000 cost savings.[35] This is a very conservative estimate and does not allow for the exceedingly high savings that are realized in off-shore drilling through the use of PDC bits. However, we believe it is not an unrealistic *average* for all oil wells drilled with PDC bits, and such a conservative estimate is appropriate for public policy purposes.

The second creative metric was to estimate how many oil and gas wells were actually drilled with PDC bits. Complicating factors are that bits may be reused, wells are not always drilled with PDC bits exclusively, PDC bits may not be used on all wells for geological reasons, and the number of wells drilled each year may vary wildly. We therefore used two point estimates – one for 1982 and one for 1992 – and then established a smooth arithmetic progression for the years in between. We estimated that in 1982, 6% of all oil wells were drilled with PDC bits.[36] For 1992, two industry experts provided virtually identical estimates – about 14% of all oil and gas wells.

Please note three points about this estimating procedure. First, as detailed in the following paragraph, it *does* take into account the cyclical nature of oil well drilling. What we are estimating is the *percentage of total wells drilled with PDC bits,* not the actual number of oil wells drilled each year. The next step of the estimation is to derive the *number* of wells drilled with PDC bits, which does reflect the annual variability in oil well drilling. Second, since 1982 marks the beginning of a "real" market for PDC bits and 1992 marks the full diffusion of the bits throughout the industry, these two years are the appropriate years with which to take point estimates on the diffusion of the bits. Third, industry analysts agree that PDC bit sales expanded

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[35] Note that averaging the point estimates to approximate cost savings is not appropriate because the published data are not randomly selected from the population of all wells drilled with PDC bits.

[36] In 1982, 3360 PDC bits were sold. Assuming that only one bit per well was used, this yields 3360 wells, or 6% of all oil and gas wells drilled in the territorial U.S. that year. This is probably a high estimate, because even in 1982 there were significant failure problems with the bits and more than one bit is used for deep drilling.

steadily throughout this 10-year period, thus a basic arithmetic progression is a reasonable way of arriving at the industry's diffusion rate (e.g., the percentage of wells drilled with PDC bits).

To calculate total second-level benefits, we therefore multiplied our estimates of the percentage of total wells drilled with PDC bits by the actual industry data on total wells drilled each year. This estimate of "PDC wells" was then multiplied by the $10,000 cost savings per well.[37] Deflated to constant 1987 dollars, total cost savings for the oil drilling industry from 1982-1992 were $340.6 million. Intangible (and unestimated) second-level benefits for the oil industry are the revenues that derive from having wells go on stream sooner than they would have using conventional bit technology.

There probably are no third-level economic impacts of much consequence from PDC bits. Beneficiaries at this level would be customers of the oil industry, namely the intermediate petrochemical industries and the transportation fuel sector. However, as an oligopoly the oil industry is not known for passing its cost savings onto its customers through lower prices (hence the windfall profits tax). We did not estimate benefits for the third level because of this. Total economic benefits from the transfer of Sandia's PDC research and software are therefore estimated at $2.2 billion ($1987).

Total Quantifiable Benefits and Costs

Sandia was not able to provide its full cost data to us at the time our study was completed; subsequent reports place the laboratory's total cost for its PDC bit program from 1973-86 at $7.5 million ($1987) (Falcone, 1995).[38]

The challenge in deriving an ultimate cost-benefit ratio for this case is in deciding how much of the total economic benefits are reasonably apportioned to Sandia National Laboratories. We believe that Sandia may be properly credited for some degree of economic impact throughout the 1982-92 period because of its significant role at all stages of the product cycle. But how much? Two clues provide guidance: Sandia's research was a critical precondition for market success, and about half of all industry references to major improvements during the diffusion stage were to Sandia publications. Based on this, we assign half of all the economic benefits to Sandia, which yields a benefit-to-cost ratio of $1.1 billion in benefits[39] to $7.5 million in costs, or 147-to-l. This benefit estimate does contain some upward bias because first-level benefits to the drill bit manufacturing industry were based on gross industry sales.

LESSONS LEARNED

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[37] For example, in 1986, our arithmetic estimate of percentage of wells drilled with PDC bits was 9.4%. Total oil and gas wells drilled in 1986 was 26,653. Thus we estimate that 2510 wells were drilled with PDC bits. If each well realizes a cost savings of $10,000, then total 1986 benefits are $25.1 million.

[38] This $7.5 million appears to represent all appropriate costs, including Sandia's R & D contracts to GE, fully-burdened R & D personnel costs, and equipment purchases greater than $10,000.

[39] To reiterate, over the 1982-92 period PDC bits generated first-level benefits of $873 million in industry sales and $982 million to the local economy. In addition, the oil drilling industry experienced second-level benefits of $340.6 million-cost savings realized by using PDC bits instead of conventional bit technologies.

One may be tempted to claim that the two technology transfers reviewed here yielded benefit-to-cost ratios of 2-to-l and 147-to-1, and that one transfer was clearly more successful than the other. We *do not* believe this is appropriate. First, benefits for PDC bits were calculated over a 10-year period for a mature industry; benefits for plasma spray were prospective, for five years, and for an industry that is only now beginning to develop. Because of these two and other differences, we offer a caution that we may not conclude that, based on these ratios, one project was more successful than the other.

Second, we would like to underscore the point that, at the end of the day, the estimation process is essentially one of judgement. Both of our estimates are simultaneously conservative and generous, and even more conservative (or generous) estimates may be arrived at with the same data. How conservative one needs to be depends largely upon the political context surrounding the analysis. We believe a good rule of thumb is that the more pressure a laboratory is under to show results, the more inherently conservative the cost-benefit estimates should be. In other words, economic generosity is in inverse relation to political need!

In addition, we recognize that some analysts may be troubled by comparing public costs to private benefits. However, we believe that there are no compelling conceptual or economic rationales for requiring only "same-sector" costs and benefits to be calculated. If we acknowledge that public sector R & D has an impact on the private economy, then there is simply no way to estimate the private return on public R & D investments without combining public and private monies in the same model. Indeed, most economic analyses of public R & D would have to be disregarded on such grounds. Since we have a real policy need to evaluate the economic impacts of the public laboratories, it seems unhelpful to reject the kind of cost-benefit analysis presented here.

We believe that there are at least four evaluation lessons to be learned from these cases:

1. It is feasible to document economic impacts associated with intangible technology transfers from public laboratories.
2. These economic impacts may be quantified using appropriate "creative metrics," published data, and point estimates based on expressed (judgemental) preferences.
3. Only benefit estimates that can be reasonably justified should be used as the basis for metrics that attempt to quantify economic impacts.
4. Public laboratories will not be able to document and estimate all of the economic benefits or costs associated with a technology transfer.

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